

THE SEARCH FOR HIGGS BOSONS: A SUMMARY*

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I summarize the prospects for discovering Higgs bosons at future pp and e^+e^- colliders both in the Standard Model and its Minimal Supersymmetric extension.

1. Introduction

In order to accomodate the well-established electromagnetic and weak interaction phenomena, the existence of at least one isodoublet scalar field to generate fermion and weak gauge bosons masses is required. The Standard Model makes use of one isodoublet: three Goldstone bosons among the four degrees of freedom are absorbed to build up the longitudinal components of the W^\pm, Z gauge bosons; one degree of freedom is left over, corresponding to a physical scalar particle, the Higgs boson.^{1,2} The discovery of this particle is the ultimate test of the Standard Model.

In the Standard Model (SM), the mass of the Higgs particle is a free parameter. The only available information is the upper limit $M_H > 63.8$ GeV established at LEP1;³ this limit can be raised to 80–90 GeV at LEP2. However, interesting constraints can be derived from assumptions on the energy range within which the model is valid before perturbation theory breaks down and new phenomena would emerge. First, if the Higgs mass were larger than ~ 1 TeV, the W and Z gauge bosons would interact strongly with each other to ensure unitarity in their scattering at high energies. Second, the quartic Higgs self-coupling, which at the scale M_H is fixed by M_H itself, grows logarithmically with the energy scale. If M_H is small, the energy cut-off Λ at which the coupling grows beyond any bound and new phenomena should occur, is large; conversely, if M_H is large, Λ is small. The condition $M_H < \Lambda$ sets an upper limit on the Higgs mass in the SM; lattice analyses lead to an estimate of about 630 GeV for this limit. Requiring that the SM be extended to the GUT scale, $\Lambda > 10^{15}$ GeV, and including the effect of top quark loops on the running coupling, the Higgs mass should be less than 180 to 200 GeV.

However, there are two problems that one has to face when trying to extend the SM to Λ_{GUT} . The first one is the so-called hierarchy or naturalness problem: the Higgs boson tends to acquire a mass of the order of these large scales [the radiative corrections to M_H are quadratically divergent]; the second one is that the simplest GUTs predict a value for $\sin^2 \theta_W$ that is incompatible with the measured one $\simeq 0.23$.

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Low energy supersymmetry solves these two problems at once: supersymmetric particle loops cancel the quadratic divergences and contribute to the running of the gauge coupling constants, correcting the small discrepancy to the observed value of $\sin^2 \theta_W$; see Ref. [4] for a review.

The minimal supersymmetric extension of the Standard Model (MSSM)^{1,4} requires the existence of two isodoublets of Higgs fields, to cancel anomalies and to give mass separately to up and down-type fermions. Three neutral, h/H (CP=+), A (CP=−) and a pair of charged scalar particles, H^\pm , are introduced by this extension of the Higgs sector. Besides the four masses, two additional parameters define the properties of these particles: a mixing angle α in the neutral CP-even sector and the ratio of the two vacuum expectation values $\tan \beta$, which from GUT restrictions is assumed in the range $1 < \tan \beta < m_t/m_b$. Supersymmetry leads to several relations among these parameters and only two of them are in fact independent. These relations impose a strong hierarchical structure of the mass spectrum, $M_h < M_Z, M_A < M_H$ and $M_W < M_{H^\pm}$, which however is broken by radiative corrections if the top quark mass is large.⁴ For instance, the upper bound on the mass of the lightest Higgs boson h is shifted from the tree level value M_Z to ~ 140 GeV for $m_t < 200$ GeV. The masses of the heavy neutral and charged Higgs particles can be expected, with a high probability, in the range of the electroweak symmetry breaking scale. Some of these features are not specific to the minimal extension and are expected to be realized also in more general SUSY models. For instance, a light Higgs boson with a mass below $\mathcal{O}(200 \text{ GeV})$ is quite generally predicted by SUSY theories.¹

The search for these Higgs particles will be a major goal of the next generation of colliders. In the following, I will briefly discuss the discovery potential of the pp collider LHC^{5,6} with a c.m. energy of ~ 14 TeV as well as a future e^+e^- linear collider^{7,8} with a c.m. energy in the range of 300 to 500 GeV. A more detailed discussion and a complete set of references can be found in Refs. [4–8] or in the review of Ref. [2].

2. Couplings and Decay Modes

In the SM, the profile of the Higgs particle is uniquely determined once M_H is fixed. The decay width, the branching ratios and the production cross sections are given by the strength of the Yukawa couplings to fermions and gauge bosons, the scale of which is set by the masses of these particles. To discuss the Higgs decay modes, it is convenient to divide the Higgs mass into two ranges: the “low mass” range $M_H < 140$ GeV and the “high mass” range $M_H > 140$ GeV.

In the “low mass” range, the Higgs boson decays into a large variety of channels. The main decay mode is by far the decay into $b\bar{b}$ pairs with a branching ratio of $\sim 90\%$ followed by the decays into $c\bar{c}$ and $\tau^+\tau^-$ pairs with a branching ratio of $\sim 5\%$. Also of significance, the top-loop mediated Higgs decay into gluons, which for M_H around 120 GeV occurs at the level of $\sim 5\%$. The top and W -loop mediated $\gamma\gamma$ and $Z\gamma$ decay modes are very rare the branching ratios being of $\mathcal{O}(10^{-3})$; however these decays lead to clear signals and are interesting being sensitive to new heavy particles.

In the “high mass” range, the Higgs bosons decay into WW and ZZ pairs, with one of the gauge bosons being virtual below the threshold. Above the ZZ threshold, the Higgs boson decays almost exclusively into these channels with a branchings ratio of 2/3 for WW and 1/3 for ZZ . The opening of the $t\bar{t}$ channel does not alter significantly this pattern, since for large Higgs masses, the $t\bar{t}$ decay width rises only linearly with M_H while the decay widths to W and Z bosons grow with M_H^3 .

In the low mass range, the Higgs boson is very narrow $\Gamma_H < 10$ MeV, but the width becomes rapidly wider for masses larger than 140 GeV, reaching 1 GeV at the ZZ threshold; the Higgs decay width cannot be measured directly in the mass range below 250 GeV.

In the MSSM, since the lightest CP-even Higgs boson h is likely to be the particle which will be discovered first, an attractive choice of the two input parameters is the set $(M_h, \text{tg}\beta)$ [with $\text{tg}\beta$ parametrizing the production cross sections]. Once these two parameters [as well as the top quark mass and the associated squark masses which enter through radiative corrections] are specified, all other masses and the angle α can be derived.

The couplings of the various neutral Higgs bosons [collectively denoted by Φ] to fermions and gauge bosons will in general strongly depend on the angles α and β ; normalized to the SM Higgs couplings, they are given by

Φ	$g_{\Phi\bar{u}u}$	$g_{\Phi\bar{d}d}$	$g_{\Phi VV}$
h	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\sin(\beta - \alpha)$
H	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos(\beta - \alpha)$
A	$1/\text{tg}\beta$	$\text{tg}\beta$	0

The pseudoscalar has no tree level couplings to gauge bosons, and its couplings to down (up) type fermions are (inversely) proportional to $\text{tg}\beta$. For the CP-even Higgs bosons, the couplings to down (up) type fermions are enhanced (suppressed) compared to the SM Higgs couplings [$\text{tg}\beta > 1$]. If M_h is very close to its upper limit for a given value of $\text{tg}\beta$, the couplings to fermions and gauge bosons are SM like. If all other Higgs bosons are very heavy, it is very difficult to distinguish the Higgs sector of the MSSM from the SM.

The lightest Higgs boson will decay mainly into fermion pairs since its mass is smaller than ~ 140 GeV. This is also the dominant decay mode of the pseudoscalar A which has no tree-level couplings to gauge bosons. For values of $\text{tg}\beta$ larger than unity and for masses less than ~ 140 GeV, the main decay modes of the neutral Higgs bosons will be decays into $b\bar{b}$ and $\tau^+\tau^-$ pairs; the branching ratios always being larger than $\sim 90\%$ and 5% , respectively. The decays into $c\bar{c}$ and gg are in general strongly suppressed especially for large values of $\text{tg}\beta$. For high masses, the top decay channels $H, A \rightarrow t\bar{t}$ open up; yet this mode remains suppressed for large $\text{tg}\beta$.

If the mass is high enough, the heavy H can in principle decay into WW and ZZ bosons but since the partial widths are proportional to $\cos^2(\beta - \alpha)$, they are strongly suppressed. For the same reason, the cascade decay of the pseudoscalar $A \rightarrow Zh$ is suppressed in general. The heavy H boson can also decay into two lighter Higgs

bosons; but these modes are restricted to very small domains in the parameter space. The branching ratios of the $\gamma\gamma$ and $Z\gamma$ decays are smaller than in the SM; this is due to the fact that the decays into $b\bar{b}$ are enhanced for $\tan\beta > 1$ and the dominant W -loop contribution is suppressed (absent) in the case of the CP-even (odd) Higgs bosons. Other possible channels are the decays into SUSY particles: while sfermions are likely too heavy to affect Higgs decays, the Higgs decays into charginos and neutralinos could eventually be important since some of these particles are expected to have masses of $\mathcal{O}(M_Z)$.

The couplings of the charged Higgs particle to fermions is a mixture of scalar and pseudoscalar currents. The charged Higgs decays into fermions but also, if allowed kinematically, into hW . Below the $t\bar{b}$ and Wh thresholds, the charged Higgs particles will decay mostly into $\tau\nu_\tau$ and $c\bar{s}$ pairs, the former being dominant for $\tan\beta > 1$. For large M_{H^\pm} and $\tan\beta$ values, the top-bottom decay $H^\pm \rightarrow t\bar{b}$ becomes dominant.

Adding up the various decay modes, the width of all five Higgs bosons remains very narrow, being of the order of 1 GeV even for large masses.

3. Production at pp Colliders

The main production mechanisms of neutral Higgs bosons at hadron colliders are the following,^{5,6}

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|-----|-----------------------------|---|
| (a) | gluon – gluon fusion | $gg \rightarrow H$ |
| (b) | WW/ZZ fusion | $VV \rightarrow H$ |
| (c) | association with W/Z | $q\bar{q} \rightarrow V + H$ |
| (d) | association with $t\bar{t}$ | $gg, q\bar{q} \rightarrow t\bar{t} + H$ |

In the most interesting mass range, $80 < M_H < 250$ GeV, the dominant production process is the gluon–gluon fusion mechanism, for which the cross section is of order a few tens of pb. It is followed by the WW/ZZ fusion processes with a cross section of a few pb; those of the associated production with W/Z or $t\bar{t}$ are an order of magnitude smaller. Note that for a luminosity of $\mathcal{L} = 10^{33}(10^{34}) \text{ cm}^{-2}\text{s}^{-1}$, $\sigma = 1$ pb would correspond to $10^4(10^5)$ events per year.

Besides the errors due to the poor knowledge of the gluon distribution at small x , the lowest order cross sections are affected by large uncertainties due to higher order corrections. Including the next to leading QCD corrections, the total cross sections can be defined properly: the scale at which one defines the strong coupling constant is fixed and the [generally non-negligible] corrections are taken into account. The “K-factors” for WH/ZH production [which can be inferred from the Drell–Yan production of weak bosons] and the VV fusion mechanisms are small, increasing the total cross sections by ~ 20 and 10% respectively; the QCD corrections to the associated $t\bar{t}H$ production are still not known. The [two-loop] QCD corrections to the main production mechanism, $gg \rightarrow H$, have been computed recently and have been found to be rather large since they increase the cross sections by a factor $\simeq 1.8$ at LHC [there is, however, an uncertainty of $\sim 20\%$ due to the arbitrariness of the choice of the renormalization and factorization scales and also of the parton densities].

The signals which are best suited to identify the produced Higgs particles at the LHC have been studied in great detail in Ref. [5,6]. I briefly summarize here the main conclusions of these studies.

For Higgs bosons in the “high mass” region, $M_H > 140$ GeV, the signal consists of the so-called “gold-plated” events $H \rightarrow ZZ^{(*)} \rightarrow 4l^\pm$ with $l = e, \mu$. The backgrounds are relatively small, and one can probe Higgs masses up to $\mathcal{O}(1 \text{ TeV})$ with a luminosity $\int \mathcal{L} = 100 \text{ fb}^{-1}$ at LHC. The $H \rightarrow WW^{(*)}$ decay channel is more difficult to use because of the large background from $t\bar{t}$ pair production.

For the “low mass” range, the situation is more complicated. The branching ratio for $H \rightarrow ZZ^*$ becomes too small and due to the huge QCD jet background, the dominant mode $H \rightarrow b\bar{b}$ is useless; one has then to rely on the rare $\gamma\gamma$ decay mode with a branching ratio of $\mathcal{O}(10^{-3})$. At LHC with a luminosity of $\int \mathcal{L} = 100 \text{ fb}^{-1}$, the cross section times the branching ratio leads to $\mathcal{O}(10^3)$ events but one has to fight against formidable backgrounds. Jets faking photons need a rejection factor larger than 10^8 to be reduced to the level of the physical background $q\bar{q}, gg \rightarrow \gamma\gamma$ which is still very large. However, if very good geometric resolution and stringent isolation criteria, combined with excellent electromagnetic energy resolution to detect the narrow $\gamma\gamma$ peak of the Higgs boson are available [one also needs a high luminosity $\mathcal{L} \simeq 10^{34} \text{ cm}^{-2}\text{s}^{-1}$], this channel, although very difficult, is feasible. A complementary channel would be the $q\bar{q} \rightarrow WH, t\bar{t}H \rightarrow \gamma\gamma l\nu$ for which the backgrounds are much smaller; however the signal cross sections are also very small making this process also difficult. The process $pp \rightarrow t\bar{t}H$ with the Higgs decaying into $b\bar{b}$ pairs seems also promising provided that good micro-vertexing to tag the b -quarks can be achieved.

In the MSSM, the situation is even more difficult. The production mechanisms of the SUSY Higgs bosons are practically the same as those of the SM Higgs; one only has to take the b quark [whose couplings are strongly enhanced for large $\text{tg}\beta$ values] contributions into account in process (a) [extra contributions from squarks decouple for high masses] and (d) [for $\text{tg}\beta \gg 1$, $q\bar{q}q \rightarrow b\bar{b}H$ becomes the dominant production process]. The various signals for the SUSY Higgs bosons can be summarized as:

i) Since the lightest Higgs boson mass is always smaller than ~ 140 GeV, the ZZ signal cannot be used. Furthermore, the $hWW(h\bar{b}b)$ coupling is suppressed (enhanced) leading to a smaller $\gamma\gamma$ branching ratio than in the SM [additional contributions from chargino and sfermion loops can also alter the decay width] making the search more difficult. If M_h is close to its maximum value, h has SM like couplings and the situation is similar to the SM case with $M_H \sim 100\text{--}140$ GeV.

ii) Since A has no tree-level couplings to gauge bosons and since the couplings of the heavy CP-even H are strongly suppressed, the gold-plated ZZ signal is lost [for H it survives only for small $\text{tg}\beta$ and M_H values, provided that $M_H < 2m_t$]. One has therefore to rely on the $A, H \rightarrow \tau^+\tau^-$ channels for large $\text{tg}\beta$ values. This mode, which is hopeless for the SM Higgs, seems to be feasible in this case.

iii) Charged Higgs particles, if lighter than the top quark, can be accessible in top decays $t \rightarrow H^+b$. This results in a surplus of τ lepton final states [the main decay mode is $H^- \rightarrow \tau\nu_\tau$] over μ, e final states, an apparent breaking of τ *vs.* e, μ universality. At LHC, H^\pm masses up to ~ 100 GeV can be probed for $m_t \sim 150$ GeV.

Thus, the search for SUSY Higgs bosons is more difficult than the search for the SM Higgs. Detailed analyses have shown that there is a substantial area in the SUSY parameter space where no Higgs particle can be found at hadron colliders.

4. Production at e^+e^- Colliders

At e^+e^- linear colliders operating in the 500 GeV energy range the main production mechanisms for Higgs particles are,^{7,8}

- (a) bremsstrahlung process $e^+e^- \rightarrow (Z) \rightarrow Z + H$
- (b) WW fusion process $e^+e^- \rightarrow \bar{\nu} \nu (WW) \rightarrow \bar{\nu} \nu + H$
- (c) ZZ fusion process $e^+e^- \rightarrow e^+e^- (ZZ) \rightarrow e^+e^- + H$
- (d) radiation off tops $e^+e^- \rightarrow (\gamma, Z) \rightarrow t\bar{t} + H$

The bremsstrahlung process is dominant for moderate values of M_H/\sqrt{s} , but falls off like $\sim s^{-1}$ at high energies. The WW fusion process, on the other hand, is more important for small values of the ratio M_H/\sqrt{s} , i.e. high energies where the cross section grows $\sim M_W^{-2} \log s$. For Higgs masses around 150 GeV, the cross sections for the bremsstrahlung and WW fusion processes are of comparable size at $\sqrt{s} = 500$ GeV, while the ZZ fusion cross section is smaller by an order of magnitude. With $\sigma \sim 100$ fb, a rate of ~ 1000 Higgs particles can be produced at a luminosity $\int \mathcal{L} = 10 \text{ fb}^{-1}$. For $M_H < 120$ GeV, the cross section for $e^+e^- \rightarrow t\bar{t}H$ is of the order of a few fb; this process can be used only to measure the $Ht\bar{t}$ Yukawa coupling once the Higgs boson is found. [Additional production mechanisms are provided by the processes $\gamma\gamma \rightarrow H$ and $e\gamma \rightarrow \nu WH$, the high energy photons generated by Compton back-scattering of laser light].

A large variety of channels can be exploited to search for Higgs particles in the bremsstrahlung and fusion processes.^{7,8} In the bremsstrahlung process, missing-mass techniques can be applied in events with leptonic Z decays and the Higgs may be reconstructed in $H \rightarrow b\bar{b}$ directly. [Missing-mass techniques of course call for collider designs in which beamstrahlung is minimal.] These techniques can be applied for Higgs masses > 100 GeV; below this value, b tagging through micro-vertex detectors must be used to separate the ZH signal from the ZZ background. The WW fusion process requires the reconstruction of the Higgs particle, while missing-mass techniques can also be used in ZZ fusion. Background events from single W and Z production restrict these experimental search techniques in the fusion channels to Higgs masses above 100 GeV.

Once the Higgs boson has been found, it will be very important to explore its properties. This is possible at great detail in the clean environment of e^+e^- colliders. The zero-spin of the Higgs particle is reflected in the angular distribution in the bremsstrahl process which asymptotically must follow the $\sin^2 \theta$ law, corresponding to the predominantly longitudinal polarization of the accompanying Z boson. Of great importance is the measurement of the couplings to gauge bosons and matter particles. The strength of the couplings to Z and W bosons is reflected in the magnitude of the production cross sections. The relative strength of the couplings to fermions is

accessible through the decay branching ratios. The absolute magnitude is difficult to measure directly; the measurement is possible only in a small mass window where the Higgs decays to $b\bar{b}$ and WW^* compete with each other. Indirect access to the top–Higgs coupling is provided by top–loop mediated photonic and gluonic Higgs decays [and the reverse processes at $\gamma\gamma$ and pp colliders]. Else, Higgs bremsstrahlung off top quarks or Higgs decays to $t\bar{t}$ pairs offer opportunities to measure the ttH coupling directly in limited ranges of the Higgs mass.

An even stronger case for e^+e^- colliders in the 300–500 GeV energy range is made by the MSSM. In e^+e^- collisions, besides the usual bremsstrahlung and fusion processes for h and H production, the neutral Higgs particles can also be produced pairwise: $e^+e^- \rightarrow A + h/H$. The cross sections for the bremsstrahlung and the pair production as well as the cross sections for the production of h and H are mutually complementary, coming either with a coefficient $\sin^2(\beta - \alpha)$ or $\cos^2(\beta - \alpha)$. The cross section for hZ production is large for large values of M_h , being of $\mathcal{O}(50 \text{ fb})$; by contrast, the cross section for HZ is large for light h [implying small M_H]. In major parts of the parameter space, the signals consist of a Z boson and a $b\bar{b}$ or a $\tau^+\tau^-$ pair, which is easy to separate from the main background, $e^+e^- \rightarrow ZZ$ [for $M_h \simeq M_Z$, efficient b detection is needed]. For the associated production, the situation is opposite: the cross section for Ah is large for light h whereas AH production is preferred in the complementary region. The signals consists mostly of four b quarks in the final state, requiring efficient $b\bar{b}$ quark tagging; mass constraints help to eliminate the QCD jets and ZZ backgrounds. The CP–even Higgs particles can also be searched for in the WW and ZZ fusion mechanisms.

In e^+e^- collisions, charged Higgs bosons can be produced pairwise, $e^+e^- \rightarrow H^+H^-$ through γ, Z exchange. The cross section depends only on the charged Higgs mass; it is large up to $M_{H^\pm} \sim 230 \text{ GeV}$. Charged Higgs bosons can also be created in laser–photon collisions, $\gamma\gamma \rightarrow H^+H^-$ but due to the reduced energy, only smaller masses than previously can be probed. The cross section, however, is enhanced in the low mass range. Finally, charged Higgs bosons can be produced in top decays as discussed above in the case of proton colliders. In the range $1 < \tan\beta < m_t/m_b$, the $t \rightarrow H^+b$ branching ratio varies between $\sim 2\%$ and 20% and since the cross section for $t\bar{t}$ production is $\mathcal{O}(0.5 \text{ pb})$ at $\sqrt{s} = 500 \text{ GeV}$, this corresponds to 200 and 2000 charged Higgs bosons at a luminosity $\int \mathcal{L} = 10 \text{ fb}^{-1}$.

The preceding discussion on the MSSM Higgs sector in e^+e^- linear colliders can be summarized in the following points: i) The Higgs boson h can be detected in the entire range of the MSSM parameter space, either through the bremsstrahlung process or through pair production. In fact, this conclusion holds true even at a c.m. energy of 300 GeV. ii) There is a substantial area of the $(M_h, \tan\beta)$ parameter space where *all* SUSY Higgs bosons can be discovered at a 500 GeV collider. This is possible if the H, A and H^\pm masses are less than $\sim 230 \text{ GeV}$. iii) In some parts of the MSSM parameter space, the lightest Higgs h can be detected, but it cannot be distinguished from the SM Higgs boson. In this case, Higgs production in $\gamma\gamma$ fusion [which receives extra contributions from SUSY particles] can be helpful.

5. Summary

At the hadron collider LHC, the Standard Model Higgs boson can, in principle, be discovered up to masses of $\mathcal{O}(1 \text{ TeV})$. While the region $M_H > 140 \text{ GeV}$ can be easily probed through the $H \rightarrow 4l^\pm$ channel, the $M_H < 140 \text{ GeV}$ region is difficult to explore and a dedicated detector as well as a high-luminosity is required to isolate the $H \rightarrow \gamma\gamma$ decay. SUSY Higgs bosons are more difficult to search for and in some areas of the MSSM parameter space, it is unfortunately possible that no Higgs particle will be found.

e^+e^- linear colliders with energies in the range of $\sim 500 \text{ GeV}$ are ideal instruments to search for Higgs particles in the mass range below $\sim 250 \text{ GeV}$. The search for the Standard Model Higgs particle can be carried out in several channels and the clean environment of the colliders allows to investigate thoroughly its properties. In the MSSM, at least the lightest neutral Higgs particle must be discovered and the heavy neutral and charged Higgs particles can be observed if their masses are smaller than $\sim 230 \text{ GeV}$. High energy e^+e^- colliders are therefore complementary to hadron colliders.

References

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